

Gamma-ray Laser and Radiation from Collimated Particles*

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The motion of channeled particles is accompanied by the photon emission. This feature can be used for the stimulated generation of high energy photons, but the required density of channeled particles must be very high.

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The radiation emitted by a fast charged particle collimated by a crystal shows the following spectrum [1,2]

$$\frac{dI}{d\omega} = e^2 \rho_{12}^2 \Delta \epsilon_{12}^2 \omega \left[1 - 2 \frac{\omega}{\omega_{max}} + 2 \left(\frac{\omega}{\omega_{max}} \right)^2 \right],$$

$$\omega_{min} < \omega < \omega_{max},$$

$$\omega_{max} = 2\Delta \epsilon_{12}^2 \gamma^2, \quad \omega_{min} = \frac{\Delta \epsilon_{12}^2}{2}, \quad (1)$$

where $\gamma = (1 - v^2)^{-1/2}$ is the relativistic factor ($\hbar = c = 1$); $e\rho_{12}$ is the dipole moment of the transition from level 2 to level 1, and $\Delta \epsilon_{12}$ is the spacing between the levels for bounded transverse motion. With planar collimation of positrons (or electrons) in a parabolic potential this spacing is $\Delta \epsilon_{12} \simeq 0.1\gamma^{1/2}$ eV ($\Delta \epsilon_{12} \simeq 10\gamma^{-1/2}$ eV for electrons); in a box potential with infinitely high walls the spacing is $\Delta \epsilon_{12} \simeq 0.1\gamma^{-1}$ eV ($\Delta \epsilon_{12} \simeq 10\gamma^{-1}$ eV) [3].

The opposite situation holds in axial collimation of electrons. In this case the spacing is $\Delta \epsilon_{12} \simeq 10\gamma$ eV [4] (the spacing between transverse levels increases with increasing particle energy), and the maximum spectral intensity increases rapidly according to the dipole approximation ($\rho_{12}\gamma\Delta \epsilon_{12} \ll 1$), since $(\frac{dI}{d\omega})_{\omega=\omega_{max}} \sim \gamma^4$ from (1).

This feature can be exploited to get induced emission of photons with an energy ~ 10 eV. The directional variation of the radiation frequency in collimation is governed by the Doppler effect [5], $\omega = \omega_0 \gamma^{-1} (1 - v \cos \theta)^{-1}$, where $\omega_0 = \gamma \Delta \epsilon_{12}$. In a laser without mirrors, in which the direction of the stimulated emission is governed by the minimum damping of the photon or the geometry of the working volume (for low damping), in the direction perpendicular to the longitudinal velocity of the particle (where the damping is low; see the discussion below) we have $\omega = \Delta \epsilon_{12} \gamma$ for electrons but $\omega = \Delta \epsilon_{12} \gamma^{-1/2}$ for positrons. At a higher energy of the electron beam it is possible, in principle, to achieve stimulated emission well into the UV region and even in the x-ray region. The beam of collimated particles must be extremely intense, as follows from the estimates below. The required conditions can probably be met for electrons.

We seek the threshold current density j_{th} required for laser action. The threshold population inversion of the particles should be [6]

$$\Delta N_{th} = (N_2 - N_1)_{th} = \frac{\tau_{12}}{\tau_c} \rho, \quad (2)$$

where τ_{12} is the time required for a spontaneous transition of a particle from state 2 to state 1, τ_c is the photon lifetime in the active region, and ρ is the number of different oscillation modes within the photon spectral line.

On the other hand, the population inversion of the particles in the channel is

$$\Delta N = j \frac{Sl}{v} (\alpha_2^2 - \alpha_1^2), \quad (3)$$

where j is the incident current density, S is the beam cross section, v is the particle velocity, $\alpha_{1,2}$ is the condition for matching the plane wave outside the crystal to the wave functions of the particle inside the crystal, $l = \min(L, l_{coh})$, L is the crystal thickness, and l_{coh} is the relaxation length for equilibrium between levels due to inelastic and thermal scattering. From (2) and (3) we find

$$j_{th} = \frac{\tau_{12}}{\tau_c} \rho \frac{v}{lS(\alpha_2^2 - \alpha_1^2)}. \quad (4)$$

The threshold population inversion ΔN_{th} is invariant against a change in the coordinate system, so we can calculate this quantity in the moving system, in which the radiation frequency is isotropic if recoil is ignored since it is governed by the radiation of a "one-dimensional" or "two-dimensional" atom. For a Lorentzian line shape, $\rho = 8\pi^2 \omega_0^3 \frac{\Delta \omega_0}{\omega_0} V'$. The emission probability in this system is $w_{12} = \frac{4}{3} \omega_0^3 e^2 \rho_{12}^2$, so that

$$\Delta N_{th} = 6\pi^2 \frac{V'}{e^2 \rho_{12}^2} \frac{\Delta \omega_0}{\tau_c' \omega_0} = 6\pi^2 \frac{V}{e^2 \rho_{12}^2} \frac{\Delta \omega_0}{\tau_c \omega_0}, \quad (5)$$

where V' and τ' are the volume of the active region and the photon lifetime in the moving coordinate system. The line width is governed primarily by the energy spread of the beam; that is, $\frac{\Delta \omega_0}{\omega_0} \simeq \frac{\Delta \gamma}{\gamma}$. Since $l \ll S^{1/2}$ for ordinary beams, only the transverse modes have the minimum damping τ_c^{-1} . With $\tau_c \sim S^{1/2} = 10^{-11}$ sec,

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$\rho_{12} = 10^{-8}\text{cm}$, $(\alpha_2^2 - \alpha_1^2) \simeq 10^{-3}$, and $E_{e-} = 100\text{ MeV}$, we find the result $j_{th} = 10^{25}\text{ particles}/(\text{cm}^2 \cdot \text{sec})$.

The value of j_{th} can be reduced, however, by reducing the energy spread of the beam. Furthermore, we can expect an important decrease in j_{th} in multilayer structures at high beam energies, in which the dipole approximation cannot be used ($\rho_{12}\gamma\Delta\epsilon_{12} \geq 1$). It can be shown that in this case the radiation emitted in the transition from one medium to another with "shaking" has the spectrum

$$\frac{dI}{d\omega} = \begin{cases} I_0 \frac{\omega}{\omega_{max}} (1 - \frac{\omega}{\omega_{max}}) [1 - 4\frac{\omega}{\omega_{max}} + 4\frac{\omega}{\omega_{max}}], \\ \omega_{min} < \omega < \omega_{max}; \\ 0, \quad \omega > \omega_{max}, \quad \omega < \omega_{min}, \end{cases}$$

where $I_0 \simeq e \frac{\Delta\epsilon_{12}}{m-\gamma\Delta\epsilon_{12}} \left| \frac{Z_2-Z_1}{Z_2} \right|$ and Z is the charge of the atoms of the medium. Assuming an energy $E_{e-} = 10^{11}\text{ eV}$, we find $\tau_{12} \sim 10^{-17}\text{ sec}$ from (6) and thus $j_{th} = 10^{19}$

particles/ $(\text{cm}^2 \cdot \text{sec})$.

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